MANX- Toward Bright Muon Beams for Colliders, Neutrino Factories, and Muon Physics

Rolland P. Johnson
Muons, Inc. (http://www.muonsinc.com/)

Abstract: New inventions are improving the prospects for high luminosity muon colliders for Higgs or Z' factories and at the energy frontier. Recent analytical calculations, numerical simulations, and experimental measurements are coming together to make a strong case for a series of devices or machines to be built, where each one is a precursor to the next. If chosen correctly, each device or machine with its own unique experimental and accelerator physics programs can drive the development of muon cooling and acceleration theory and technology. This strategy can achieve an almost unlimited program of experimental physics based on the cooling and acceleration of muon beams. The very first step of the program is to develop stopping muon beams by using a 6D muon cooling segment (momentum-dependent Helical Cooling Channel with emittance exchange using a homogeneous energy absorber) to test the theory and simulations and to improve the mu2e experiment.

Ultimate Goal:
High-Energy High-Luminosity Muon Colliders

- precision lepton machines at the energy frontier
- achieved in physics-motivated stages that require developing inventions and technology, e.g.
  - **MANX**
    - demonstrate HCC, HS, & EEX concepts
  - **high-intensity proton driver**
    - simultaneous intense muon beams
  - **stopping muon beams**
    - useful 6D cooling w HCC, EEX
  - **neutrino factory**
    - HCC with RF, RLA in CW Proj-X
  - **Z’ factory**
    - low Luminosity collider, HE RLA
  - **Higgs factory**
    - extreme 6D cooling, low beta, super-detectors
  - **energy-frontier muon collider**
    - more cooling, lower beta
LEMC Scenario

1.5 TeV LEMC

4 km ILC linac
103 GeV/pass

30 GeV Coalescing ring

30 GeV RLA

\( \mu^- \) cool/accel

\( \mu^- \) cap/cool

Target

\( \mu^+ \) cool/accel

\( \mu^+ \) cap/cool

8 GeV proton accumulator and buncher rings

Dogbone Scheme

Muons, Inc.
Simulation study of HCC for Muon Collider (MC)

Yonehara talk
### Muons, Inc. Project History

<table>
<thead>
<tr>
<th>Year</th>
<th>Project</th>
<th>Expected Funds</th>
<th>Research Partner</th>
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Underlined are explicitly related to HCC ~$3.5M spent, $1.3M left.

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Rol - Feb. 3, 2009
AAC Meeting
Principle of Ionization Cooling

- Each particle loses momentum by ionizing a low-Z absorber
- Only the longitudinal momentum is restored by RF cavities
- The angular divergence is reduced until limited by multiple scattering
- Successive applications of this principle with clever variations leads to small emittances for many applications
- Early work: Budker, Ado & Balbekov, Skrinsky & Parkhomchuk, Neuffer
The equation describing the rate of cooling is a balance between cooling (first term) and heating (second term):

\[
\frac{d\varepsilon_n}{ds} = -\frac{1}{\beta^2} \frac{dE_\mu}{ds} \varepsilon_n + \frac{1}{\beta^3} \frac{\beta_\perp (0.014)^2}{2E_\mu m_\mu X_0}
\]

Bethe-Bloch  
Moliere (with low Z mods)

Here \(\varepsilon_n\) is the normalized emittance, \(E_\mu\) is the muon energy in GeV, \(dE_\mu/ds\) and \(X_0\) are the energy loss and radiation length of the absorber medium, \(\beta_\perp\) is the transverse beta-function of the magnetic channel, and \(\beta\) is the particle velocity.

Note that \(\frac{d\varepsilon_n}{\varepsilon_n} \approx -\frac{dE_\mu}{E}\) which implies a \(~1.5\) GeV linac for \(10^{-6}\).
Ionization Cooling is only transverse. To get 6D cooling, emittance exchange between transverse and longitudinal coordinates is needed.

**THIS RH CONCEPTUAL PICTURE BE REALIZED? A MANX GOAL!**
Helical Cooling Channel

Continuous, homogeneous energy absorber for longitudinal cooling
Helical Dipole magnet component for dispersion
Solenoidal component for focusing
Helical Quadrupole for stability and increased acceptance

BNL Helical Dipole Siberian Snake magnet for AGS spin control
Two Different Designs of Helical Cooling Magnet

- Siberian snake type magnet
- Consists of 4 layers of helix dipole to produce tapered helical dipole fields.
- Coil diameter is 1.0 m.
- Maximum field is more than 10 T.

- Helical solenoid coil magnet
- Consists of 73 single coils (no tilt).
- Maximum field is 5 T
- Coil diameter is 0.5 m.

Great new Kashikhin-Yonehara innovation!
6-Dimensional Cooling in a Continuous Absorber

- Helical cooling channel (HCC)
  - Continuous absorber for emittance exchange
  - Solenoidal, transverse helical dipole and quadrupole fields
  - Helical dipoles known from Siberian Snakes
  - z- and time-independent Hamiltonian
  - Derbenev & Johnson, *Theory of HCC*, April/05 PRST-AB
Muons, Inc.

**Particle Motion in a Helical Magnet**

Combined function magnet (invisible in this picture)
Solenoid + Helical dipole + Helical Quadrupole

Dispersive component makes longer path length for higher momentum particles and shorter path length for lower momentum particles.

Opposing radial forces
\[ F_{h\text{-dipole}} \approx p_z \times B_\perp; \quad b \equiv B_\perp \]
\[ F_{\text{solenoid}} \approx -p_\perp \times B_z; \quad B \equiv B_z \]

Transforming to the frame of the rotating helical dipole leads to a time and z – independent Hamiltonian

\[ \kappa = \frac{2\pi a}{\lambda} = \frac{p_\phi}{p_z} \]

\[ b' \text{ added for stability and acceptance} \]
Some Important Relationships

Hamiltonian Solution

\[ p(a) = \frac{\sqrt{1+\kappa^2}}{k} \left[ B - \frac{1+\kappa^2}{\kappa} b \right] \]
\[ k = 2\pi/\lambda \quad \kappa = ka \]

Equal cooling decrements

\[ q \equiv \frac{k_c}{k} - 1 = \beta \sqrt{\frac{1+\kappa^2}{3-\beta^2}} \quad k_c = B\sqrt{1+\kappa^2}/p \]

Longitudinal cooling only

\[ \hat{D} \equiv \frac{p}{a} \frac{da}{dp} = 2 \frac{1+\kappa^2}{\kappa^2} \quad q = 0 \]

~Momentum slip factor

\[ \eta = \frac{d}{d\gamma} \frac{\sqrt{1+\kappa^2}}{\beta} = \frac{\sqrt{1+\kappa^2}}{\gamma \beta^3} \left( \frac{\kappa^2}{1+\kappa^2} \hat{D} - \frac{1}{\gamma^2} \right) \]
\[ \frac{\kappa^2}{1+\kappa^2} \hat{D} \sim \frac{1}{\gamma_{\text{transition}}} \]
HCC Virtues

New concept
not FODO, but based on a theory (theory by Derbenev)
time and z-independent Hamiltonian
solenoid, helical dipole, helical quad fields
two versions: with or without RF

Large acceptance
for huge muon beam emittances
large resonance driving terms

Homogeneous field
minimal resonant losses
DE/E for a million in 6D reduction implies a long channel

Many uses for muon beams (overview by Mary Anne)
Example of longitudinal cooling in a HCC overcomes $1/\beta^2$ dependence of energy loss to keep the momentum spread small while undergoing energy degradation to slow a muon beam.

MERIT-like targetry into NF/MC Front End up to End of Energy/Phase Rotator into HCC w/o RF w/ tapered LiH wedges variably spaced to match energy loss while maintaining reference radius of 50 cm. The z value refers to depth from start of HCC.
Example of HCC use for the mu2e experiment discussed by Ankenbrandt and Yonehara
Beam cooling to reduce the size of a muon beam depends on the magnetic field strength. The Phase II proposal to develop this hybrid scheme has been approved. Here a hybrid magnet of Nb3Sn (green) and HTS (red) could provide up to 30 T in an HCC design.
many new ideas under development:

- H$_2$-Pressurized RF Cavities
- Continuous Absorber for Emittance Exchange
- Helical Cooling Channel
- Parametric-resonance Ionization Cooling
- Reverse Emittance Exchange
- RF capture, phase rotation, cooling in HP RF Cavities
- Bunch coalescing
- Very High Field Solenoid magnets for better cooling
- p-dependent HCC precooler
- HTS for extreme transverse cooling
- MANX 6d Cooling Demo
- improved mu2e design

See [http://www.muonsinc.com/](http://www.muonsinc.com/) “papers and reports”

42 Abstracts for PAC09
21 Papers from EPAC08
13 Papers from PAC07
MANX, A 6D MUON BEAM COOLING EXPERIMENT

Robert Abrams\textsuperscript{1}, Mohammad Alsharo’a\textsuperscript{1}, Andrei Afanasev\textsuperscript{1}, Charles Ankenbrandt\textsuperscript{1}, Emanuela Barzi\textsuperscript{2}, Kevin Beard\textsuperscript{1}, Alex Bogacz\textsuperscript{3}, Daniel Broemmelsiek\textsuperscript{2}, Yu-Chiu Chao\textsuperscript{3}, Linda Coney\textsuperscript{4}, Mary Anne Cummings\textsuperscript{1}, Yaroslav Derbenev\textsuperscript{3}, Henry Frisch\textsuperscript{5}, Ivan Gonin\textsuperscript{2}, Gail Hanson\textsuperscript{4}, David Hedin\textsuperscript{6}, Martin Hu\textsuperscript{2}, Valentin Ivanov\textsuperscript{1}, Rolland Johnson\textsuperscript{1}, Stephen Kahn\textsuperscript{1}, Daniel Kaplan\textsuperscript{7}, Vladimir Kashikhin\textsuperscript{2}, Moyses Kuchnir\textsuperscript{1}, Michael Lamm\textsuperscript{2}, James Maloney\textsuperscript{6}, Michael Neubauer\textsuperscript{1}, David Neuffer\textsuperscript{2}, Milord Popovic\textsuperscript{2}, Robert Rimmer\textsuperscript{3}, Thomas Roberts\textsuperscript{1}, Richard Sah\textsuperscript{1}, Pavel Snopok\textsuperscript{4}, Linda Spentzouris\textsuperscript{7}, Melanie Turenne\textsuperscript{1}, Daniele Turrioni\textsuperscript{2}, Victor Yarba\textsuperscript{2}, Katsuya Yonehara\textsuperscript{2}, Cary Yoshikawa\textsuperscript{1}, Alexander Zlobin\textsuperscript{2}

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\textsuperscript{7}Illinois Institute of Technology

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Overview of MANX channel

- Use Liquid He absorber
- No RF cavity
- Length of cooling channel: 3.2 m
- Length of matching section: 2.4 m
- Helical pitch $\kappa$: 1.0
- Helical orbit radius: 25 cm
- Helical period: 1.6 m
- Transverse cooling: $\sim$1.3
- Longitudinal cooling: $\sim$1.3
- 6D cooling: $\sim$2

Most Simulations use G4Beamline (Muons, Inc.) and/or ICOOL (BNL)
HS for Cooling Demonstration Experiment

Goals: cooling demonstration, HS technology development
Features: SSC NbTi cable, $B_{\text{max}} \sim 6$ T, coil ID $\sim 0.5$m, length $\sim 10$m
Prototype coils for MANX have been designed and modeled. Construction of a 4-coil assembly using SSC cable is complete. Tests in the TD vertical Dewar are complete. Since the MANX matching sections are made of coils with varying offset, they are more expensive than the cooling region. Consequently the total magnet cost can be drastically reduced if the matching sections are not needed. See talk by Kashikhin.
Simpler Option without Matching Sections

Magnet ~$10M
LHe or LH2 region
Matching sections

Magnet < $5M
Requires transverse displacement of downstream spectrometer & has additional engineering challenges
Summary: MANX

- **Will Test:**
  - Theory of Helical Cooling Channel (HCC)
    - p-dependent HCC with continuous absorber
  - Helical Solenoid Magnet (HS) and absorber
    - similar to those required to upgrade the mu2e experiment
  - Simulation programs (G4BL, ICOOL)

- **Encourages wider interest in muon cooling for Fermilab’s future**
  - Adds Energy Frontier and Stopping Muon Beam HEP Experimenters
  - Local universities especially important
  - RAL and MICE connect to European and Asian communities

- **Minimizes costs and time**
  - no RF, uses normalized emittance, ~5 m LHe E absorber
  - builds on MICE, improves 6-D capability, ~ps detectors
  - RF is developed in parallel with new concepts

- **Collaborators have been asked to address AAC charge:**
If successfully executed does the MANX proposal provide a validation of 6-D ionization cooling, based on requirements for a Muon Collider. What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?

- Collection, cooling, extreme cooling, transport, acceleration of muon beams for MC
- Require several new techniques and technologies
- MANX demonstrates a new HCC approach to cooling large emittance beams
  - Homogeneous magnetic fields can cope better with resonances
- MANX demonstrates a new method of emittance exchange

If successfully executed does the MANX proposal provide a validation of an upgrade of the mu2e experiment based on a collection scheme that reduces “flash” deadtime and the use of the ionization-cooling energy-absorber to range out hadronic backgrounds? What does the Committee view as the optimum mix of simulations and experimental demonstration required to provide such validations?

- Degrading the higher momentum, higher flux part of $\pi$ and $\mu$ production spectra
  - Gets higher mu/proton, without magnetic mirrors that imply a long flash gate
- Longitudinal cooling with EEX concentrates the stopping beam in the target while
- Hadronic backgrounds are ranged out (also reduces flash gate time)
• What are the primary technical risks within the MANX proposal and are they appropriately mitigated through the development period?
  • Timely commitment of manpower and funds
  • MICE delays
  • Engineering escalations for additional capabilities beyond liquid helium
    • vacuum, hydrogen E degrader
    • with Individually powered coils: power supplies, SC leads,

• Given the anticipated timelines within the Muon Five-year Proposal and the mu2e development plan, what is the appropriate schedule for implementation of MANX, either at Fermilab or at RAL?
  • To follow MICE at RAL, coordination and continuity are required
  • Sooner would be better

• Do the MANX resource requirements appear reasonably estimated?
  • Iteration on 4-coil design will improve magnet estimates
  • Cryostat, power supplies, matching sections, reuse of MICE detectors, designs

• Can the MANX approach to a mu2e upgrade impact the outlook for Project X?
  • If the energy absorber approach works,
    • higher mu flux is possible, and higher p flux required
## AAC Agenda

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<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
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<tbody>
<tr>
<td>8:30-8:50</td>
<td>Slava Derbenev</td>
<td><strong>Theory of the HCC</strong></td>
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<td>Mary Anne Cummings</td>
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<td>for MC, NF, and mu2e</td>
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<td>9:10-9:35</td>
<td>Chuck Ankenbrandt</td>
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<td>Vladimir Kashikhin</td>
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